A 3D Hand Motion Capture Device with Haptic Feedback for Virtual Reality Applications

Javier Torres-Sanchez, Salvatore Tedesco, Brendan O'Flynn

Abstract—**In this paper, the challenges associated with the design of new generation hand motion capture devices for Virtual Reality (VR) applications are described. The need for developing a hand motion capture device with tactile feedback that integrates all the sensors and actuators associated with VR, while meeting the latency requirements is introduced. A detailed description of functional and non-functional specifications is also given.**

Finally, a comparison study with commercially available technology is provided highlighting that the proposed device compares favorably not only in terms of functional parameters, such as connectivity, integration of sensors and actuators, and latency, but also in terms of non-functional parameters, e.g., no need to wash, ambidextrous features and modularity.

I. Introduction

As opposed to traditional video gaming, users in a Virtual Reality (VR) scenario wear a head-mounted display (HMD), move and create their own visual motion. Actions from the users, in direct interaction with the visual input, include head movements, reaching, touching or lifting virtual objects. The vestibular sense responds to movements of the head and gravitational forces and, in general, contributes to the sense of balance or equilibrium [1]. Proprioception (e.g. perception of body position by the users), on the other hand, involves sensory information coming from the muscles; the brain receives this information and constructs an overall sense of the position and motion of the body [1]. Thus, proprioception is related to the sense of the effort that needs to be made to reach or lift an object. Additionally, once a virtual object is reached, the tactile sense (e.g. the sense of touch where contact, pressure or traction exerted on the skin are recognized) fulfills its role.

Haptic technology is an emerging interdisciplinary field that deals with the understanding of human touch (human haptics), motor characteristics (machine haptics), and with the development of computer-controlled systems (computer haptics) that allow physical interactions with real or virtual environments through touch [2]. Even though, traditional human–computer interfaces (HCI) have delivered types of stimuli that are based on two senses (vision and sound), with the addition of the sense of touch through tactile and force feedback, the computer-based applications become richer in media content through better mimicry of real-life situations and tasks or remote real environments [2].

Because of the abovementioned aspects, VR controllers, in particular those targeting hand motion, are required which include a large number of sensors and actuators, to provide information about the joint angles and 3D hand positioning, acceleration or tactile feedback. In addition, any mismatch between visual, vestibular, proprioception, tactile senses, and user expectations will degrade the user experience and may also cause VR sickness [3], whose symptoms include general discomfort, headache, nausea, fatigue or disorientation. To avoid this, VR systems require latencies significantly lower than traditional video gaming in the order of 100 Hz.

There are a number of data gloves [4] that capture hand motion while meeting the VR latency requirements which can be found nowadays in the market. Those data gloves are designed for a variety of applications, going from classical manufacturing, robotics, entertainment, and sign languages [5], to more recent scenarios involving healthcare, and in particular motor rehabilitation [6-7], medical training [8], and ergonomics. The introduction of gaming aspects in those applications is also a trending characteristics required to support end-users' engagement.

Likewise, haptic feedback [9] gloves are also available, although their latency can be considered excessive for VR.

Data gloves are still among one of the most widely input device adopted in applications involving VR, together with pads and controllers, and allow continuous recording of hand joint angles. Despite the massive attention researchers have in this area [10], and the number of devices already on the market, major limitations still appear. Those drawbacks include portability, need of a cloth-support, poor robustness, poor durability, calibration required when the glove is worn by new users, and cost. Moreover, commercial devices overcoming these limitations may be not suitable for applications requiring high accuracy and performance.

The solution envisioned, designed and manufactured at the Tyndall National Institute incorporates the level of sensing hardware and software required to provide low end-to-end latency with haptic feedback in a robust, modular, easy to use/wear/wash form factor, also incorporating ergonomic design. The described glove is a third generation iteration of the system developed by the authors, as described in previous work [11-12]. The goal being to develop a data glove more accurate than commercial devices, and also more natural and easy to use than controllers. This paper describes the development of a 3D hand motion capture device with haptic feedback for VR applications. The ambition is to

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Authors are with the Tyndall National Institute, University College Cork, Cork, Ireland. Emails: javier.torres@tyndall.ie; brendan.oflynn@tyndall.ie; salvatore.tedesco@tyndall.ie

create an input device that transports the hands into the virtual world amplifying the immersive experience for the user. A brief outline of the envisaged whole system is illustrated in Section II. The description of the data glove and its components is given in Section III, while particular focus on the functional and non-functional requirements to be met is provided in Section IV. Also, functioning of the embedded software is covered in Section V. Finally, Section VI depicts a comparative study between the developed glove and commercial devices discussing the main differentiations. Conclusions and future works are drawn in Section VII.

II. System Design

Figure 1 shows a flowchart of the overall system. The data glove represents the main VR input device on which the VR platform is built. User requirements define the hardware design of the data glove system as well as the system requirements related to device architecture, communication, and data interpretation of the sensor readings, which are essential for the development of motion algorithms. The software stack is available on the VR platform connected wirelessly to the data glove, including data abstraction and gesture recognition layers. Those layers integrate the embedded software in the data glove, in order to collect, gather, and parse the input data received from the device and pass it to higher levels of the software stack incorporating gesture recognition and visualization. As an example, Figure 2 shows a Unity3D demonstration that manages the collection / processing of data from the HCI data glove device and, using a model of the hand, mimics the hand movement in real-time. This work mainly focuses on the description of the development of a novel 3D data glove device with haptic feedback for VR applications, with a discussion on the functional and non-functional requirements met.

III. VR Glove Description

The Tyndall VR Glove is a 3D hand motion capture device with haptic feedback, able to meet the sensor/actuator integration and latency requirements for VR applications. The ergonomics and human factors engineering incorporated in the glove have been critical for the development of the system. It has been designed to be robust, rugged, modular and intuitive to use. Figure 3 shows the visual of the device, as it was envisaged at the initial conceptual stage.

The system consists of two independent units:

- Control unit

The control unit (Figure 4), integrates all the electronics that for sensing or actuation principles is not required to be physically on the fingers. This includes the microcontroller, battery management, memory, and wireless communication technologies. As shown in Figures 3-4, an adjustable wrist strap is used to fasten the unit to the hand. One side of the unit is placed on the wrist, while the other side is placed on the back of the palm. The flexible bridge between the two parts conforms to the angle of the wrist. This unit also provides the connections for the units that are deployed on the fingers, e.g. the finger sensing units.

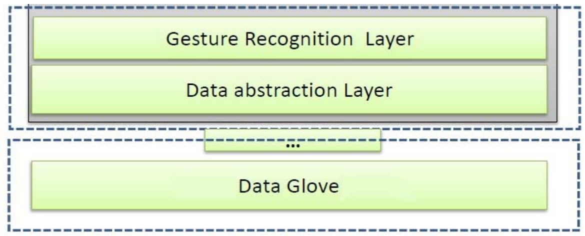

Fig. 1 System design

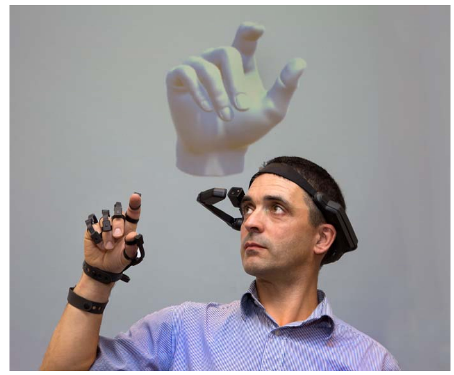

Fig. 2 System demo (data glove + Unity 3D VR platform)

Fig. 3 Device vision

Fig. 4 The Control unit of the system

- Finger Sensing units

The finger sensing unit, shown in Figure 5, is the part of the device that is placed on the fingers. The electronics in this part is kept minimal and includes the required sensors and actuators.

The design follows a modular approach, the finger sensing unit is plugged into the control unit through standard USB modules and, as shown in Figure 6, it slides on to the rings placed on the fingers, with the sensors/actuators part landing on the finger bones and the flexible cables/interconnections crossing the joints.

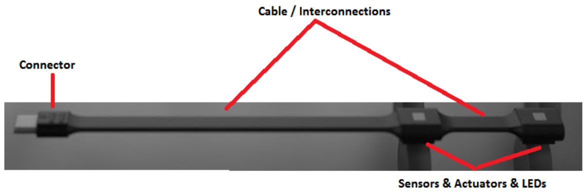

Fig. 5 Sensing unit of the system

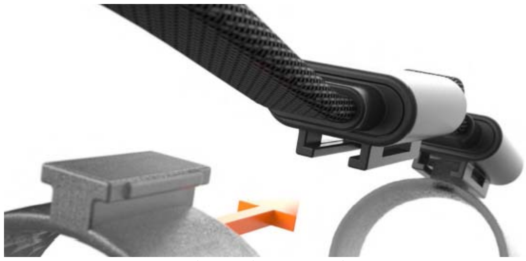

Fig. 6 Finger attachment

IV. VR Glove Specifications

A. *Hardware Functional Specifications*

The functional specifications considered during the development of the Tyndall VR Glove are described below.

- **Hand/Finger joint angles tracking**: The device integrates two inertial measurements units (IMUs) per finger sensing unit (Figure 5), and two IMUs on the control unit (one on the back of the palm and another one on the wrist), in order to account for the hand degrees of freedom and estimate the wrist joint angle, proximal interphalangeal (PIP) and the metacarpophalangeal (MCP) joints (Figure 7). Overall, there are 12 IMUs integrated in the data glove. Each IMU consists of a triaxial accelerometer, triaxial gyroscope, and triaxial magnetometer. The orientation of the IMU is estimated as a result of well-known sensor fusion algorithms (for example, [13]), and the relative orientation of the IMUs with respect to each other is used to obtain the specific joint angles.

- **Hand 3D positioning**: The device integrates 11 Infrared (IR) LEDs, two per sensing unit and an additional one on the wrist, to enable 3D positioning of the hand. The sensing unit LEDs can also be used as an alternative source of information for the joint angles calculation. Approaches for 3D tracking and gesture recognition of LED-based gloves are shown in [14-16].

- **Wireless/Wired communications and connectivity**: The following standards are included in the system

  - WLAN, compliant to IEEE 802.11 a/b/g/n;
  - Bluetooth, compliant to dual-mode Bluetooth V4.0;

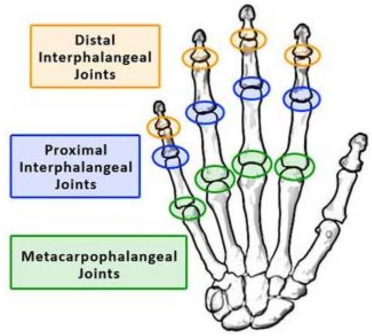

Fig. 7 Fingers joints

  - USB, fully compliant with the On-The-Go Supplement to the USB 2.0 Specification;

This feature provides the device with high throughput wireless communication (Wi-Fi, Bluetooth, USB 2.0) as well as low-power approaches, in particular, Wi-Fi low-power modes and Bluetooth Low Energy (BLE). In addition, this broad range of communication options enables connectivity with a number of generally used and popular devices, including tablets, phones, laptops and smart TVs.

- **Processing capability**: The device integrates a 32-bits microcontroller with built-in single precision floating point unit [17]. Memory and speed capabilities are shown in Table I.

- **Power consumption**: Given the low latency requirements, and the large number of sensors, LEDs, and vibration actuators, the system power consumption can be substantially high depending of the usage of these features especially as for the vibration actuators and LEDs. The device integrates a 1200mAh Lithium polymer battery. When the device operates in high throughput mode, with no Wi-Fi power savings enabled, and all the fingers active, the battery supports the system operations for at least 2 hours, ranging from 2 to 5 hours depending on the actuators usage. The battery is rechargeable through the available micro USB port at the back of the control unit, with the USB port also providing wired communication.

- **Sensors**:

  - 12 IMUs , two per finger, one on the wrist, and an additional one on the back of the palm;
  - 11 IR LEDS, two per finger and one on the wrist. Each LED is driven from a dedicated Pulse Width Modulation (PWM) channel.

- **Actuators**: The data capture glove integrates ten vibration actuators, 2 per finger sensing unit, to provide haptic feedback. The system provides an overall haptic feedback latency of less than 2 ms and each sensing unit pair of actuators is controlled independently.

- **Memory**: On-board EEPROM 512 Kb to facilitate the store of calibration parameters

- **RGB LED**: This can be used for providing status indication to the user, such as “Connection Established” or “Calibration Performed”.

- **Latency**: Latency is an important factor in VR applications and, as a general rule, the lower the latency the better the user experience. Since the Oculus Rift refresh rate is set to 90 Hz [18], the initial implementation of the device aimed to reach 100 Hz end-to-end throughput (or, equivalently, 10 ms latency) including all the following data processing:
  - Sampling the 12 IMUs;
  - Performing the real-time sensor fusion algorithms to estimate the IMUs orientation;
  - Performing real-time, automated hard/soft-iron compensation [19] for every IMUs;
  - Transmitting the outcome wirelessly to an external device for display.

As shown in Table I, it is visible that the Tyndall VR Glove meets the latency, memory footprint, and processing capability required by the application using only a fraction of its full potential. It is, therefore, expected that even lower latencies are potentially achievable.

TABLE I. VR GLOVE PROCESSING CAPABILITY

Proposed VR Glove	**Processing Capability**		
	Capability	***Used***	***% Usage***
Flash	2 MB	107 KB	5 %
RAM	256 KB	35 KB	14 %
Speed	Max 180 MHz	48 MHz	27 %

B. *Non-Functional Specifications*

The non-functional specifications considered during the development of the Tyndall VR Glove are described below.

- **Aesthetics**: The aesthetics of the device is inspired by well-known VR head-mounted devices, such as the Oculus Rift [18] or HTC Vive [20], with which the Tyndall Glove could be paired.

- **Comfort and breathability**: The device is mounted on the hand and does not use fabrics or sensors directly attached on the fingertips, which indicates that the glove is comfortable to wear for end-users for long periods, even in the order of hours. As shown in Figure 3, the device is breathable and it does not cause significant hand sweat. As a consequence, end-users are also able to interact with physical devices outside of the virtual world and perform other tasks (i.e. typing on the keyboard, drinking from a glass, etc.) while still comfortably wearing the device.

- **No need to wash**: As there are no fabrics, there is no need to wash the system. Readily available pre-saturated IPA wipers can be used for general cleaning.

- **Easy to wear**: The control unit is placed on the wrist and the back of the palm by means of a removable strap. As illustrated in Figure 6, sensing units slide onto the rings to attach the sensing units to the fingers. With this approach, users are able to quickly put on and take off the gloves. Also, the rings can have different size in order to accommodate for different users’ hand size without the need to change any other part of the glove.

- **Modular and easy to customize**: Finger sensing units can be plugged in and out, and thus only be used if required by the application. Therefore, users can also customize their solution adopting only the desired fingers (for instance, only the thumb and index fingers) for certain applications.

- **Right/Left handed**: Designed to be ambidextrous, availing of the modularity of the device, it can be used for both, right and left hands, by plugging the sensing units corresponding to the thumb into the correct side of the control unit.

- **Hand sizes**: Able to accommodate different hand sizes by adjusting the ring sizes and the wrist strap.

V. EMBEDDED SOFTWARE

The SW embedded in the Tyndall HCI glove implements all the necessary drivers and application code to read simultaneously from all the IMUs and perform the real-time sensor fusion algorithms. Those algorithms are requested to estimate IMUs orientation and perform, in real-time, automated magnetic calibration [19] for every IMUs. This calibration is essential for a good accuracy of the orientation algorithm in order to compensate for hard/soft-iron effects due to surrounding ferromagnetic materials. The calibration is performed on-board and involves specific hand movements. During the use of the data glove, quality checks are executed in real-time and, if needed, a new calibration routine may be requested, indicated to the user through a modification of the LED status.

The data is wirelessly transmitted to the VR platform and includes the orientation of each sensor expressed via quaternion representation, as well as timestamps and raw data from the accelerometers, gyroscopes and magnetometers. A flow diagram of the Embedded SW is shown in Figure 8.

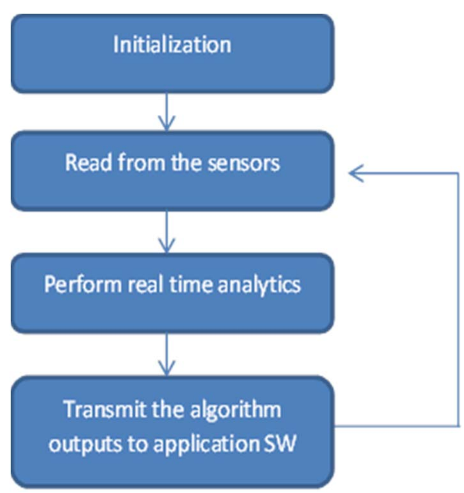

Fig. 8. Embedded SW Application flowchart

Finally, incoming data packets from the VR platform are processed to enable and configure the amplitude, frequency and duration of haptic events.

The real-time algorithms that run in the embedded firmware have been designed and optimized specifically for low-latency real-time operation in low-power embedded systems with limited systems resources in terms of memory footprint and clock frequency.

VI. COMPARATIVE STUDY

The device has been successfully designed, manufactured, encapsulated, and tested (Figure 9). The device at the current stage is fully functional and meets all the specifications given in Section IV and outlined in Table II. The unit controller is 11 x 5.5 cm and weighs 63.3 g, while each finger sensing unit is 20 x 1 cm and weighs 10.1 g. Thus, the final device, completely encapsulated and equipped with battery has an overall weight below 114 g. Characteristics evident in Table II/Figure 9 provide an overall picture of the current stage of the developed device and show the route for potential improvements in the following stages, such as higher dynamic accuracy, automatic magnetic calibration, and deeper manufacturability design.

Table II compares the presented solution developed at Tyndall National Institute with the top alternative products currently available in the market, e.g. Perception Neuron Glove [21], Synertial IGS Gloves [22] and NeuroDigital Technologies's Avatar VR Glove [23]. The IGS 16 sensors option has the greatest number of IMUs (without considering an optional sensor on the wrist), but this is because the system also includes sensors on the fingertips (except on the pinky), which was avoided during the Tyndall Glove design to enhance user comfort and ability to interact with other physical devices and perform other tasks.

The Tyndall VR Glove is the only one that integrates IR LEDs. This additional feature can be used for 3D positioning or to improve the accuracy of the running on-board sensor fusion algorithms. Haptic feedback is one of the main features of NeuroDigital gloves, but the reported feedback latency (20 ms) is significantly above when compared to the Tyndall Glove (2 ms). Moreover, the designed system is the only one integrating Wi-Fi, classic Bluetooth, BLE, and USB communications. Although Synertial claims their gloves to be ambidextrous, it should be noted that this is achieved by physically detaching the electronics from the glove-cloth, which can be cumbersome for the users.

In terms of system end-to-end latency, all the solutions appear to be suitable for VR applications and able to meet Oculus Rift's frame rate, which was taken as the industry standard. Sensor fusion algorithms are generally implemented on-board. As for the commercial products, it is not clear whether additional algorithms, such as hard/soft-iron magnetic interferences compensation, are performed and are embedded. It is worth underlying that the accuracy level reported for the Tyndall Glove is the result of preliminary tests performed in a lab-environment without using gold-standard technologies, e.g. camera-based systems. In these preliminary tests, the data glove was strapped to a wooden hand with adjustable finger joints. The static angle for each hand/finger joint was measured through a goniometer. In the dynamic scenario, the fingers had a fixed position and the wooden hand was moved randomly in the 3D space with homogeneous magnetic conditions so that, ideally, the joint angles were supposed to be constant during the movement and the variation of the estimated joint angles were analyzed. Indeed, orientation accuracy obtained via sensor fusion algorithms is always relative to test conditions, which include the presence of possible magnetic interference, the type of motion (low/high dynamics), etc. For these reasons, the values reported in Table II should be taken for indication purpose only. Therefore, information on the accuracy of marketed gloves is not generally reported (except for the static case with the Perception Neuron glove). Even though a hard/soft-iron magnetic compensation algorithm has been developed for running on-board, its analysis is out of the scope of the present paper and further studies are needed to investigate the effects of magnetic distortions on the VR Glove's accuracy performance in dynamic scenarios.

Fig. 9. The manufactured device

VII. CONCLUSION AND FUTURE WORKS

This paper describes the development of a novel 3D hand motion capture device with haptic feedback for VR applications. A full description of the features has been given and a comparison with commercially available technology has been provided. The VR Glove compares favorably not only in terms of functional parameters, such as connectivity, sensors/actuators integration, and latency, but also in terms of non-functional parameters, e.g. no need to wash, ambidextrous features, and modularity. As a part of future works, additional studies will be performed in order to quantify accuracy against gold-standard technologies, and potentially, novel orientation algorithms will be investigated to reduce the estimation error of the system. Finally, we are currently working on completing the prototype of the VR game. We plan to design a study so that the whole system could be evaluated by end-users in terms of responsiveness, accuracy, understandability, comfortability, etc. Those outcomes will be useful to define the potential application of the developed data glove in different gaming scenarios, from entertainment to healthcare (e.g. stroke rehabilitation monitoring).

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TABLE II. GLOVE COMPARATIVE ANALYSIS

	Tyndall Haptic VR Glove	**Perception Neuron**	**Synertial IGS Gloves**	**NeuroDigital Technologies**
No of IMUs (finger, palm, wrist)	(2, 1, 1) – 12 IMUs overall	(2, 1, 1) – 12 IMUs overall	(3, 2, 1) except for pinky fingertip – 17 IMUs overall	(1, 1, 0) – 6 IMUs overall
IR LEDs	Yes - 2 per finger and one on wrist	No	No	No
Haptics – Feedback Latency	10 actuators – Latency < 2 ms	No	No	10 actuators – Latency > 20 ms
Wi-Fi	IEEE 802.11 a/b/g/n	Yes	Yes	No
Bluetooth	Dual mode 4.0 (Classic and BLE)	No	No	Bluetooth 4.0
USB	On-The-Go USB 2.0	USB 2.0	No	USB 2.0
Ambidextrous	Yes	No	Yes, detachable electronics	No
Fabrics	No	Yes	Yes	Yes
Modular	Yes	Yes	No	No
Adaptable to hand sizes	Yes	Yes	Yes, detachable electronics	No
End-to-End Latency	100 Hz tested. ~250 Hz expected	60-120 Hz	Max 500 Hz. Standard 240/120 Hz	Unknown
Static Accuracy (Roll, Pitch, Yaw)	± (0.5 , 0.5 , 2) deg	± (1 , 1 , 2) deg	Unknown	Unknown
Battery Duration	From 2 to 5 hours with low latency	USB powered	Unknown	Unknown
On-board Algorithms	Sensor fusion, hard/soft-iron compensation	At least sensor fusion	At least sensor fusion	Unknown

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